TECHNICAL MEMO

Evaluation of the Applicability of Thermal-Enhanced Recovery at the Former Manufacturing Plant

Date: October 4, 2018

Sherwin-Williams submitted the Draft *Feasibility Study, Former Manufacturing Plant Area, Sherwin-Williams Hilliards Creek Site* (FMP FS; ELM Group, 2018) to the United States Environmental Protection Agency (EPA) in May 2018. In its August 2018 comments, the EPA suggested that in situ thermal remediation (ISTR) technologies may have applicability at the FMP. In a September 6, 2018 meeting with EPA and the New Jersey Department of Environmental Protection (NJDEP), Sherwin-Williams discussed the possible outcome of evaluating ISTR as a remedial technology at the FMP based on the five balancing criteria. On September 12, 2018, the EPA requested that Sherwin-Williams provide a formal technical memorandum assessing the viability of ISTR to remove residual light non-aqueous phase liquids (LNAPL) from the subsurface at the FMP.

This technical memo leverages information provided by relevant guidance from EPA (EPA, 2018, 2014, 2012, 2008, 2006, 1997,1995a), US Army Corps of Engineers (USACE, 2014), ESTCP (ESTCP, 2010a, 2010b, 2009), and academia (Munholland, 2016) (Vidonish, 2016) (Heron, 2015) (Zhao, 2014) as well as from thermal remediation patent holders like TerraTherm (TerraTherm, 2018) (Griepke, 2018), site-specific technical documents (EHS Support, 2017, 2018) (ELM Group, 2018), and other resources such as those listed in the References and Bibliography section of this technical memorandum to:

(a) Describe the site-specific factors that influence the selection and use of thermal remediation technologies at the site.
(b) Evaluate the most likely thermal remediation alternative based on site-specific factors.
(c) Identify the implementation concerns associated with thermal remediation at the site.

This technical memo discusses the following considerations in relation to potential utilization of thermal enhanced LNAPL recovery:

1. What is the Conceptual Site Model (CSM) for the area(s) where ISTR would potentially be applied?
2. What is ISTR, and which technology would be used if applied at the FMP?
3. What and where are the main factors likely to limit/prevent effective thermal-enhanced LNAPL recovery at the site?

1 LNAPL CSM: Characteristics, Distribution, and Fate and Transport

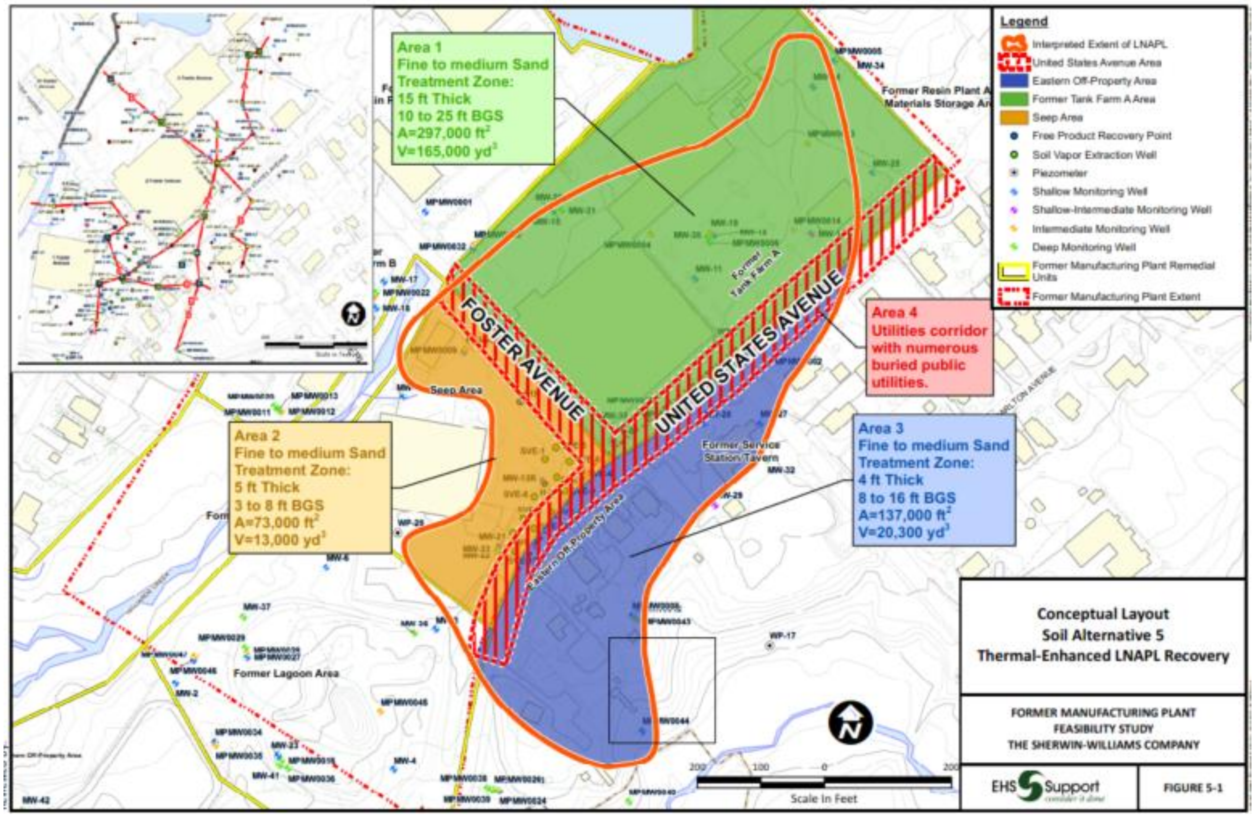
A detailed discussion of the LNAPL conditions in the subsurface is provided in the *LNAPL Investigation Report* (LNAPL CSM; EHS, October 2018) and this information is summarized in the FMP FS. LNAPL is present in portions of four contiguous areas of the FMP, as shown on the Figure 5-1 on the following page:

- Area 1, the former Resin Plant and Tank Farm A Area;
- Area 2, the Seep Area;
- Area 3, the Eastern Off-Property Area; and
- Area 4, United States Avenue and Foster Avenue.

Each of these areas possess unique characteristics that affect the ability to use ISTR as a remedial technology.

In the context of the September 6, 2018 discussion with EPA and in consideration of the logistical constraints at the site, the most likely area for application of thermal remediation is Area 1 (the former Resin Plant/Tank Farm A area), located west of US Avenue and north of Foster Ave. Thermal remediation is not a likely candidate for the other three areas due to the following factors:

- Area 2: As discussed in the FMP FS, the accessibility of the LNAPL supports the use of excavation as the most viable remedial alternative.
- Area 3: This is primarily a residential area and the LNAPL saturations are low in comparison to those in Areas 1 and 2, supporting the conclusion that a less intrusive technology, such as bioremediation, may be most appropriate. Additionally, use of thermal remediation in these areas would likely damage homes and utilities.
- Area 4: These are roadways with subsurface utilities. Use of thermal remediation in these areas would require the closure of the roadways and would likely severely damage the utilities.



(adapted from EHS Support, 2018)

The key conditions and physical attributes to consider in the assessment of thermal treatment in Area 1 are as follow:

LNAPL Characteristics

- The LNAPL is comprised of weathered mineral spirits with some limited mono-aromatic constituents co-eluted in the LNAPL mixture.
- Mineral spirits is predominantly comprised of aliphatic petroleum hydrocarbons in the C9 – C12 range with some heavy molecular weight petroleum hydrocarbons up to C16 comprising less than 5% of the mass.
- Key physical attributes of the LNAPL that are important to thermal technical evaluations include:
  - Initial Boiling Point: 145 to 175 ºC
  - Final Boiling Point: 220 ºC
  - Autoignition Temperature: 240 ºC
  - Vapor Pressure: 0.6 mm kPa at 20 ºC
  - Vapor Density: 4.5 to 5 (air density = 1)

The high initial and final boiling points of mineral spirits and the high vapor density are important considerations in the implementation of thermal remediation. EPA has commented that in the presence of groundwater, co-boiling would likely occur at lower temperature such as 85 to 95 ºC. However, the majority of constituents in mineral spirits (even with co-boiling) will not boil at these lower temperatures, with mass loss occurring through partitioning of mass into vapor due to temperature elevation. Given the vapor density and high boiling points, this will be a rate limiting step controlled by vapor pressures and diffusion. In this context, heating will need to be prolonged to maximize treatment efficiencies at this site.

Carbon Weight	Alkane	Initial Boiling Point (ºC)
C9	Nonane	151
C10	Decane	174
C11	Undecane	193
C12	Dodecane	216

To address these key limitations on thermal treatment of this LNAPL, higher temperatures (consistent with those provided by conductive heating as described below) will be required to accelerate remediation time frames and limit the residual mass post treatment. However, despite this and considering inefficiencies with heat transfer and potentially inaccessible areas (which cannot be treated), residual hydrocarbon mass will be present (post treatment) which will require further remediation via natural attenuation processes. None of the bacteria characterized at the site are thermophiles and as a result, the thermal remediation activities will result in sterilization of the soil (and associated bacteria consortia) which will significantly stunt natural attenuation processes.

LNAPL Distribution

The LNAPL is typically first encountered at or slightly above the water table at depths of approximately seven to ten feet below ground surface. The LNAPL extends another ten to fifteen feet into the saturated zone. On the west side of Area 1, the LNAPL is found at a shallower depth, approximately four feet below ground surface.

The LNAPL extends over approximately seven acres. This area includes the 2 Foster Avenue/3 United States Avenue building, approximately one-half of the 4 Foster Avenue building, the adjacent paved parking areas, and portions of the lawn area north of the former Tank Farm A area.

The saturated soil where the LNAPL is located is a fine-grained silty sand unit. The impacts are contained within an unconfined groundwater system and, as such, any steam production associated with thermal remediation activities will occur at near atmospheric pressure (some localized pressure will develop but will rapidly dissipate).

LNAPL Fate and Transport

The LNAPL CSM found that the LNAPL across the majority of the site is at or below residual saturation levels, with rising and falling water table levels, natural source zone depletion and manual recovery activities serving as key contributors to the low LNAPL saturations at the site. Imbibition testing (application of high pore water pressures to the soil cores) found that even under high pressures, no

LNAPL was displaced from the soil pore matrix. These findings supported a conclusion that the LNAPL in the majority of the area is neither recoverable nor mobile.

The LNAPL CSM also concluded that the LNAPL was undergoing biodegradation. This conclusion was supported by the presence of methane beneath the floor slabs of the 2 and 4 Foster Avenue buildings and the adjacent parking areas as well as the heat signature of the groundwater in which the degradation is occurring. Literature values of several hundred to several thousand gallons per acre per year of LNAPL depletion were cited as providing a representative range of the possible natural source zone depletion occurring at the FMP. The Phase II investigation (Assessment and Qualifications of In-Situ Biodegradation) found that the depletion rates in the former Resin Plant/Tank Farm A area were likely limited by the absence of key nutrients such as nitrogen and phosphorous.

Finally, the LNAPL CSM concluded that dissolved-phase constituents originating from the LNAPL were undergoing biodegradation. This was subsequently confirmed by the results of the Phase II investigation, which were included as an appendix to the final LNAPL report.

2 Thermal Remediation Technology Description and Screening

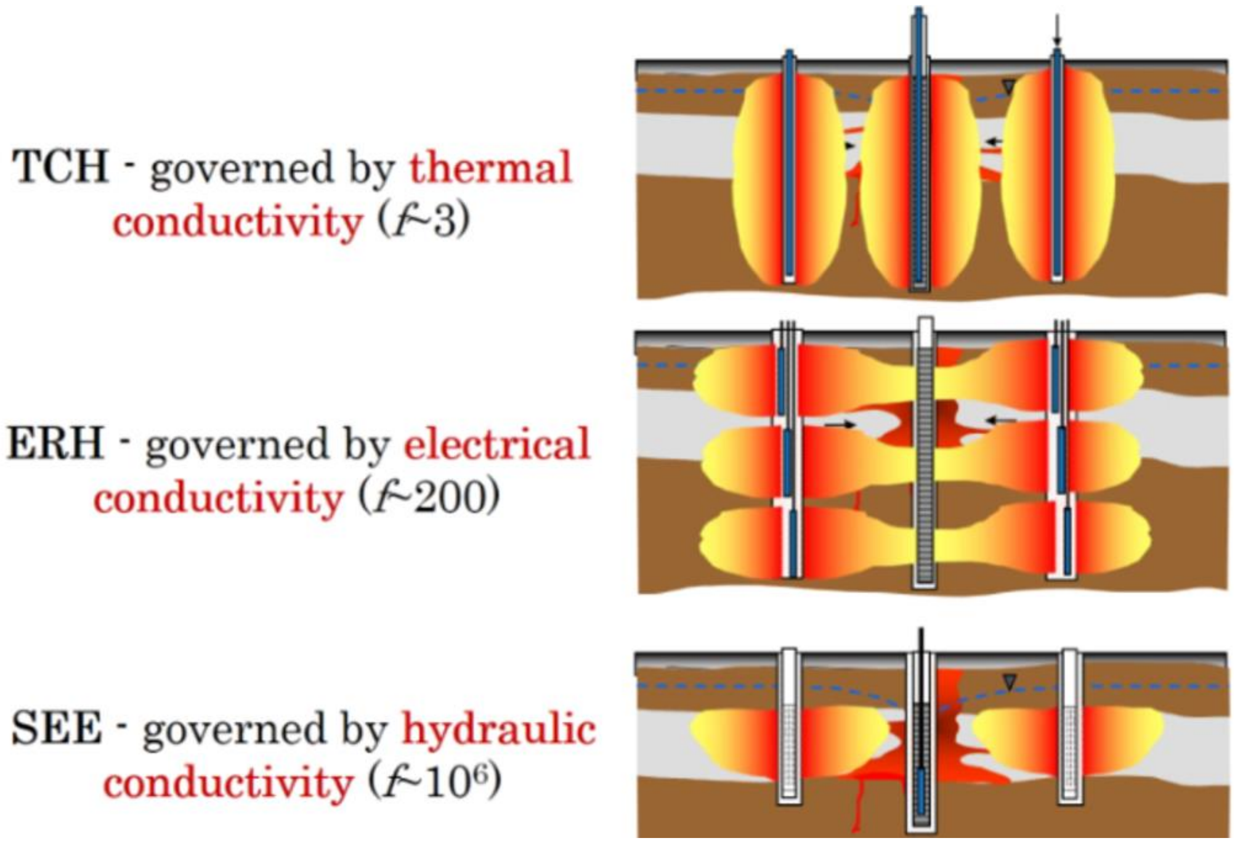
Various synonymous nomenclature for ISTR includes thermal remediation, in situ thermal treatment (ISTT), in situ thermal desorption (ISTD), thermally enhanced remediation, thermally enhanced soil vapor extraction (SVE), thermal enhanced recovery, heat enhanced LNAPL extraction, and other variations. The key concept function is to heat the subsurface LNAPL to boiling, which converts the LNAPL to gas or vapor that is subsequently captured by vacuum extraction and then reclaimed and/or treated at the surface.

Three primary heating methods are used in thermal remediation. These are:

- TCH - Thermal Conduction Heating (electric or gas generators)
- ERH - Electrical Resistance Heating (electric)
- SEE - Steam Enhanced Extraction (gas)

Regardless of the heating and extraction method selected, infrastructure to recover and collect the LNAPL, steam and hydrocarbon vapors must be installed. Based on the size of the area, the volumes of steam generated from heating and the volumes of air that must be moved to capture vapors, the size of this infrastructure would be significant, with hundreds of extraction wells (a thermal remediation vendor has indicated up to 500) and major treatment equipment for condensing water and hydrocarbons, and treating water and hydrocarbon vapors. The magnitude of this equipment, wells and piping will pose some significant logistical concerns at the site

The three typical heating patterns are illustrated below:



(adopted by permission from Griepke, 2018)

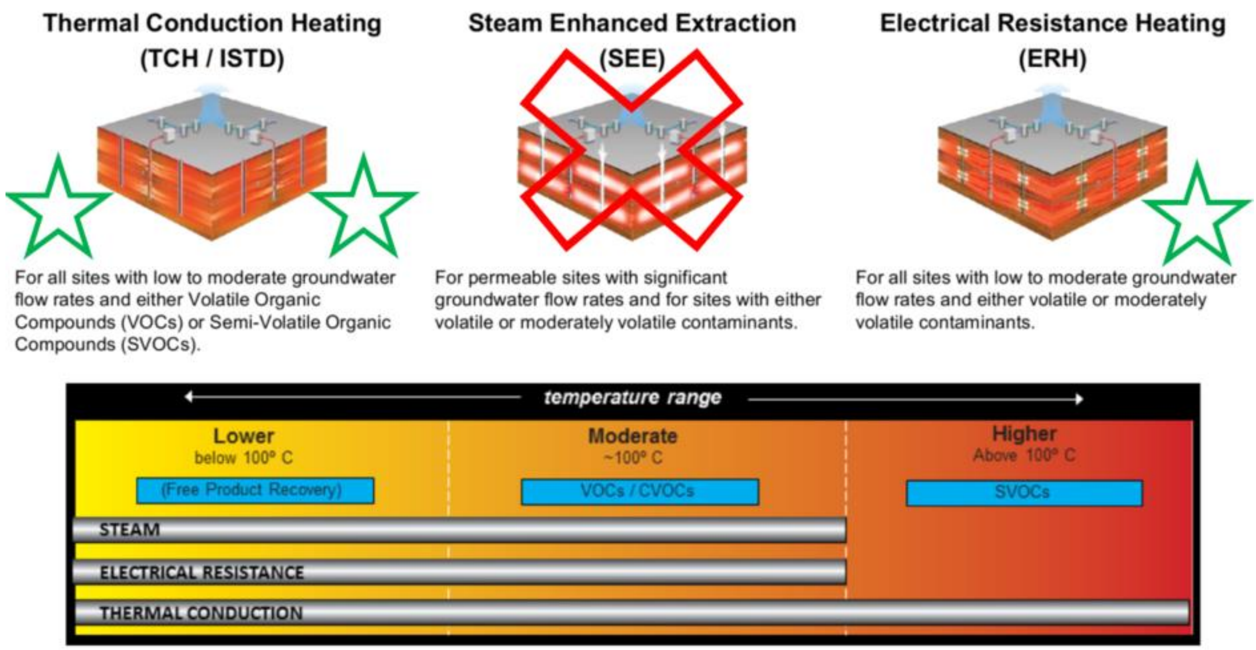
Consistent with guidance provided by EPA, USACE, ESTCP, and others, the selection of best thermal-enhanced LNAPL recovery method, and its effectiveness, is governed by five key factors:

- **Target chemicals** – At the site the target chemical(s) is mineral spirits LNAPL, which contains constituents with boiling points greater than 100^o C.
- **Geology and hydrogeology** – The target treatment zones at the site are characterized as unconfined, reasonably uniform silty sand down to >25 feet below ground surface; where unsaturated vadose zone varies from 7 to 10 feet thick above the fresh (not saline) groundwater table that varies seasonably from 2 to 5 feet; presenting nominal groundwater flux (Darcy flux or Darcy velocity) of 0.02 ft/day.
- **Depth and size** – The target treatment depth at the site is the mineral spirits LNAPL smear zones down to 25 feet below ground surface. Area 1, as shown on draft Figure 5-1 above, is approximately 300,000 ft^2 (about 7 acres) and consists of a treatment volume of about 165,000 yd^3.
- **Location (proximity to above ground structures, buried utilities, etc.)** – Adjacent to the area are Foster Avenue and United States Avenue, where subsurface utilities are present. The 2 and 4 Foster Avenue and 3 U.S. Avenue buildings are present on the site.
- **Availability of sufficient energy** – Enough energy (usually electricity) must be available directly at the site. If sufficient electricity is not available from the local electric utility, then electric generators are used to supply the electrical deficit. For example, reasonable expectation for electricity service demand for a 7-acre thermal remedy at the site is on the order of 7,500 kW

and 9,000 kVA (TerraTherm, 2018). Additional evaluation is needed to assess whether this is available from the utility or if supplemental generating capacity would be needed.

Based on the physical properties of the LNAPL (as described above) and the site conditions, a technology that can maintain temperatures above 100° C is needed to achieve LNAPL mass removal. Since there is no confining unit that would create subsurface pressures greater than atmospheric pressure, the boiling points will be consistent with those observed under atmospheric conditions. Maintaining temperatures greater than 100 ºC at the heater wells will allow for more efficient heat conduction without the number of wells becoming too excessive.

Consistent with the guidance provided by a thermal remediation vendor (as shown in the figure below), thermal conduction heating is considered the most suitable means to achieve the required temperatures in the subsurface at the site and most even treatment across the affected areas.

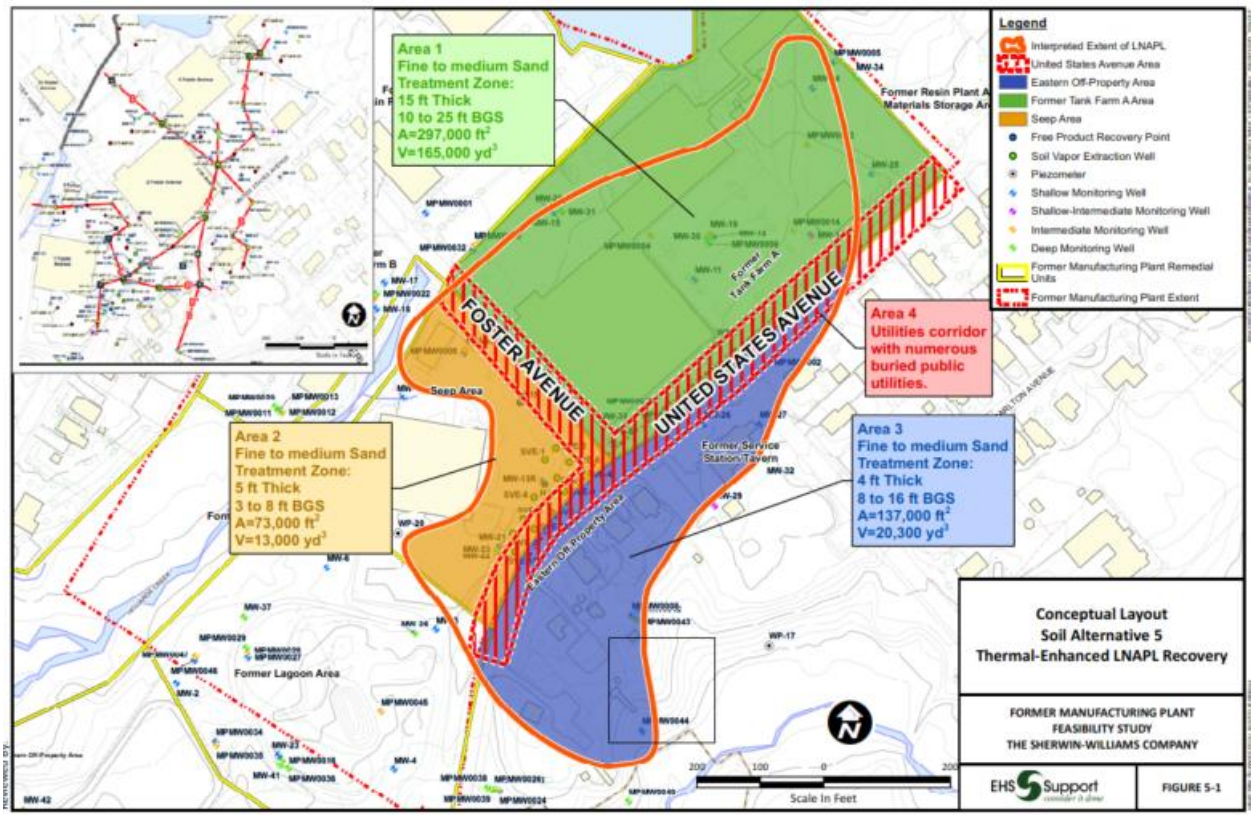


Other key considerations in selecting thermal conduction heating over SEE and ERH include:

- Steam Enhanced Extraction is not considered viable here due to a number of factors including the shallow nature of groundwater, the hydraulic properties of the soils and the presence of silt interbeds. This all will result in uneven heating and a highly variable flow of steam in the subsurface, which will cause inefficient treatment and may cause daylighting of steam, resulting in potentially dangerous impacts to adjacent landholders.
- Electrical Resistance Heating was identified as having a number of constraints including: an inability to reach desired temperatures for treatment and uneven heating and inefficient treatment due to soil properties and subsurface utilities.

3 Implementation of Thermal in Area 1 and Preliminary Evaluation of Balancing Criteria

As noted above, Thermal Conductive Heating is identified as the thermal remedial technology that would likely be used in Area 1. As shown in the Figure below, Area 1 is a very large area (7 acres; 297,000 ft^2) and abuts areas of sensitive infrastructure (including public utilities in Foster Avenue and United States Avenue) as well as having proximal sensitive receptors (residents to the south-east and a police station to the south-west of the treatment area). As a result, an evaluation of thermal remediation as a remedial alternative in a FS will find significant issues with short-term effectiveness, implementability and cost.



(adapted by permission from EHS Support, 2018)

It is important to note that while there is no theoretical upper limit on how much of an area can be subjected to a shallow thermal remedy, today's practical definition of a "large" TCH thermal remedy is on the order of 3 to 5 acres. In this context, treatment of this area will have major logistical constraints associated with provision of services (electricity), logistics and traffic. Again, these considerations will translate to significant concerns with short-term effectiveness, implementability and cost in a FS.

The potentially large size of a thermal remediation in Area 1 is supported by discussions with TerraTherm, a thermal remediation vendor, who noted that their largest TCH project to date is about 3.2 acres in Teterboro, NJ (Heron, 2015), as shown below:

TCH
Teterboro, New Jersey
3.2 Acre and 102,000 cy

(adopted by permission from Griepke, 2018)

Based on review of the literature and discussions with thermal vendors, several location specific impediments to TCH implementation at the FMP have been identified:

- Above ground buildings over the target treatment zone would require removal. None of these buildings are owned by Sherwin-Williams.
- Residential areas adjacent to the thermal treatment area may be affected by vapor and steam migration, and construction of a thermal project on this scale would be a substantial nuisance to the residents.
- Buried utilities in the adjacent roadways and within the treatment area could be damaged or could act as preferential conduits for migration of steam and vapors into buildings. These utilities serve not only the commercial buildings in the treatment area, but also the adjacent residential properties.
- The high temperatures needed to remove the LNAPL could deform or damage roadways or lose structural integrity when heat is applied to the subsurface.
- Silver Lake, a major recharge feature, would cause steeper gradients and facilitate an influx of cold water into the treatment areas, limiting treatment efficiency.
- Thermal remediation will result in sterilization of soils within the treatment area and potentially adjacent areas, impacting the effectiveness of MNA post treatment and biological remediation activities in the adjoining areas.

The evaluation supports a conclusion that, although thermal remediation could be performed in Area 1, the potential magnitude of impacts and risks to the community eliminate it from serious consideration when another viable alternative is available. A detailed summary of potential impacts on the remedy and risks to sensitive receptors, along with the applicable FS criteria the site-specific condition would affect, are captured in the table below, along with an assessment of significance in the context of this site. Please note that the FS evaluation criteria include consideration of both the balancing criteria that would be evaluated in the FS as well as the modifying criteria that EPA would consider following comments on the Proposed Plan.

Site Condition/Key FS Criteria	Significance and/or Risk
Need to remove above ground buildings and structures Balancing Criteria: • Short-Term Effectiveness • Implementability • Cost	**High** - In the treatment area all buildings and structures would have to be removed to facilitate installation of heater wells and other remediation activities. These buildings and structures are not owned by Sherwin-Williams and it is uncertain whether the current property owner would want these structures removed.
Damage to public roads Balancing/Modifying Criteria: • Short-Term Effectiveness • Community Acceptance	**High –** Proximity of roads to the thermal treatment area will result in subterranean heating of pavements and deformation of surfaces. This could result in cracking, settlement, and establishment of pot holes and sink holes in the road structures abutting the treatment areas. Associated with these impacts are related nuisance and road safety concerns for the community.
Impacts on community policing activities Balancing/Modifying Criteria: • Short-Term Effectiveness • Community Acceptance	**High –** The police station is in close proximity to the treatment area and could be affected by steam, vapors and or associated utility and road integrity impacts noted in this table. This likely would require relocation of the police station to ensure that community policing activities are not affected.
Damage to buried public utilities in roadway corridors Balancing/Modifying Criteria: • Short-Term Effectiveness • Implementability • Community Acceptance	**Very High** – The proximity of heating areas could have a major impact on buried utilities in US Avenue and Foster Avenue. These utilities could become inoperable or fail, leading to additional risks including explosion and fire. Key sensitive utilities identified include: • Polyethylene gas lines which would be subject to deformation and loss of integrity above 65ºC (based on manufacturer specifications) • Telecommunications cables which have temperature ratings below 50 ºC and critically have impedance specifications that can also be impacted by temperature • Conductive metal water pipes that can conduct heat and lead to heating or worse boiling of water supplies to existing buildings and residences.
Damage to buried utilities in treatment area	**High** – These utilities which connect to public utilities could become damaged and as a result

Balancing Criteria: • Short-Term Effectiveness • Implementability	impact on public utilities. Where practical these will have to be capped and removed, but identification of all utilities and appropriate termination will be problematic.
Thermal desiccation of soil and potential for settlement Balancing Criteria: • Short-Term Effectiveness • Implementability	**Moderate to High** – Assuming buildings and structures are removed from the site (and therefore cracking of on-site buildings and structures is not a concern), the heating of soils and removal of water content will result in consolidation and settlement. This could have major impacts on inflexible services such as water pipes, sewers and stormwater pipes (especially collared fittings which may become disconnected) as well as road pavements where differential settlement will occur.
Traffic and noise impacts on the community during construction. Balancing/Modifying Criteria: • Short-Term Effectiveness • Implementability • Community Acceptance	**High** – The scale of construction activities associated with the TCH treatment option in Area 1 will be large, requiring provisioning of a major electrical supply to the site and the drilling of nearly 1,000 wells (heater wells and extraction wells) and major construction activities associated with piping. In addition, the system would be operating 24 hours a day, 7 days a week with the potential for noise and lighting nuisance associated with these activities.
Visual impacts on the community during operation. Balancing/Modifying Criteria: • Short-Term Effectiveness • Implementability • Community Acceptance	**High –** In terms of thermal remediation, a large amount of electrical wiring, piping and infrastructure will be installed above grade. To support this Sherwin-Williams will have to fence the area and provide 24/7 security and lighting to preclude vandalism and theft of electrical wiring and equipment. The associated visual nuisance of such a fenced and lighted site and continuous activities will create some significant impacts on adjacent residential properties.
Steam and vapor migration risks to adjacent residential area Balancing/Modifying Criteria: • Reduction of toxicity, mobility or volume through treatment • Short-Term effectiveness	**Very High** – While extraction of vapor and steam will be conducted at the site, sensitive receptors are in very close proximity to the treatment area. Risks to receptors are exacerbated by the presence of basements in the residential properties and utilities (water, sewer, etc.) entering into the buildings, the presence of public

• Implementability • Community Acceptance	utilities adjacent to the treatment area that may allow preferential flow of vapors, biogenic gases (methane) and steam into buildings and structures. This may pose both a nuisance, a fire/explosion risk (with methane gases) and an inhalation exposure risk from hydrocarbons.
Nuisance associated with heating of water pipes. Balancing/Modifying Criteria: • Short term Effectiveness • Implementability • Community Acceptance	**Moderate to High** – Water service is provided to the commercial and residential areas by pipes within Foster Avenue and United States Avenue. The proximity of the treatment area and heating dynamics will lead to the heating of these utilities including water supplies, which may boil in pipes, impact appliances connected to cold water supplies or result in risks to residents.
Thermal treatment may negatively impact ongoing bioremediation occurring in adjacent areas. Balancing Criteria: • Long Term Effectiveness • Short Term Effectiveness	**Moderate to High**: Soil excavation and enhanced bioremediation is proposed for adjacent areas of the site. Further natural processes may be utilized to remediate residuals within the thermal treatment areas. The high temperatures associated with TCH will result in sterilization of microbial populations and impede future biological degradation rates. Based on the slow groundwater seepage velocities under ambient conditions, recolonization of areas will be slow with thermal treatment temperatures sufficient to sterilize even spore forming bacterial populations.
High electricity demand could impact on local users. Balancing/Modifying Criteria: • Implementability • Community Acceptance • Cost	**Moderate to High** – An assessment of electrical demands for the project indicates that around 8,000 kVA will be required to heat the area. It is unlikely that the existing electrical infrastructure can support this demand, and it is uncertain whether the Gibbsboro municipal utility(s) can provide sufficient electricity (grid power). Major upgrades to electrical infrastructure are anticipated throughout the area and this will impact schedule and potentially lead to additional interruption and disturbance for residents. Further, such large demand in a non-industrial area may result in grid stability concerns which could impact electrical supply to other users in the area.

Thermal treatment will result in the discharge of heated groundwater into Hilliards Creek, with potential impacts on aquatic receptors. Balancing Criteria: • Short-Term Effectiveness • Implementability	**High:** Thermal treatment will result in heating of groundwater that will discharge to Hilliards Creek. During periods of low flow this incremental increase in temperature would affect aquatic and benthic organisms downstream of the treatment location.

4 Summary

An assessment of thermal treatment technologies for Area 1 of the FMP concluded that Thermal Conductive Heating would be the likely heating technology if thermal treatment was applied at the FMP. Key considerations included application temperatures (which provided a high level of potential treatment), geology and hydrogeology and site implementability.

An evaluation of site-specific conditions, including the proximity of the residential area and Hilliards Creek, the presence of public utilities in adjacent roadways, and the presence of buildings on the site were considered to be major constraints limiting the applicability of this technology.

Based on the evaluation in this memorandum, it is concluded that if thermal treatment was to be included as a remedial alternative in the FS, it would not be ranked highly in comparison to an alternative that would consist of bioremediation/biostimulation combined with focused LNAPL removal. This conclusion is based on a preliminary evaluation of the balancing and modifying criteria:

- Long-Term Effectiveness and Permanence: Thermal treatment and the combined remedy would rank similarly for this criterion. Both technologies would remove LNAPL from Area 1. However, residual LNAPL would remain after application of thermal treatment and would need to be addressed via bioremediation.
- Short-Term Effectiveness: Thermal treatment would rank very low as a result of the very significant impacts on the nearby residential area, subsurface utilities, adjacent roadways, Hilliards Creek and buildings in the treatment area.
- Reduction in Toxicity, Mobility or Volume Through Treatment: Although thermal treatment would reduce the volume of LNAPL within the actual treatment area, it would negatively affect the ongoing biodegradation within and around the treatment area. Therefore, it would rank low for this criterion.
- Implementability: Thermal treatment would rank very low for this criterion as a result of the presence of buildings that would need to be removed, the large scale of the project, and the need for the very large infrastructure needed to supply electricity, heat the subsurface and manage the produced steam, vapors and LNAPL.
- Cost: Thermal treatment is expected to rank low for this criterion. Although no formal cost estimate has been prepared, a reasonable estimate of the potential costs would be $200 - $300 per cubic yard, based on discussions with vendors. Based on the estimated treatment volume of soil, the cost for thermal treatment in Area 1 would be more than $30 million.

- Community Acceptance: Given the significant impacts on the community, it can be predicted that, if thermal treatment was included in a Proposed Plan, it would not be acceptable to the community.

In summary, thermal treatment is not a technology suited to the site-specific conditions at the FMP and would not rank highly in a formal FS evaluation. Therefore, it is not recommended for inclusion as a remedial alternative in the FMP FS.

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